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**Article**

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# Direct normal irradiance predictions using broadband models for Indian stations

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**Abstract**

In this paper three parametric models CPCR2, MLWT2 and REST have been used to compute direct normal irradiance (DNI) for five Indian stations, namely New Delhi, Pune, Jaipur, Kolkata and Mumbai. Computed values of DNI have been compared with measured values in terms of percentage root mean square error (RMSE) and percentage mean bias error (MBE). It is observed that the average percentage RMSE for the year is the minimum for MLWT2 model for Jaipur followed by New Delhi and Pune and the values are 1.67%, 2.33% and 2.49%, respectively. But for coastal stations Kolkata and Mumbai the corresponding minimum values occur for CPCR2 model and REST model respectively, and the values are 2.62% and 2.76%, respectively. It shows that MLWT2 model performs better for most of the Indian stations except the coastal stations.


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*Keywords:* Direct normal irradiance; Root mean square error; Mean bias error

## 1. Introduction

Several authors including [1] has explained in their work that the solar energy systems are more energy efficient under cloudless conditions. Under such conditions, most of the solar radiation is in the form of direct radiation. Many devices, like solar concentrators, use only the direct component of the solar radiation.

Network of direct irradiance measuring stations is rather scarce throughout the world and the same is true for India as well. One way of knowing direct radiation at normal incidence, also called direct normal irradiance (DNI), is to measure global and diffuse radiation on horizontal and then convert these values into DNI, by using zenith angle. Another way is to use a pyrheliometer and measure DNI directly. In India, DNI is measured by using pyrheliometer only at four synoptic hours: 9:30, 11:30, 13:30 and 15:30, and this too at few stations only. There is too much paucity of DNI data in India and this necessitates the development of theoretical models to predict DNI under different atmospheric conditions. In the present work as explained in the earlier work by Narain [1], it has been

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assumed that there is no cloud cover and predictions are made under different amount of water vapor, ozone content and humidity etc.

Many authors have worked along these lines. Solar radiation models for predicting the average daily and hourly global radiation, beam radiation and diffuse radiation have been reviewed by Power [2]. Parameterization Model C has been discussed by Iqbal [3]. King and Buckius [4] have explained direct solar transmittance for a clear sky, that accurately predicts the variation with fundamental quantities. Direct irradiance model, has been explained by Bird and Hulstrom [5]. The parameterized model for global radiation under partially cloudy skies has been explained by Choudhary [6]. As explained by Kotti et al. [7] that the direct solar irradiance can also be accurately calculated from global and diffuse horizontal irradiance measurements after correcting the diffuse irradiance values. In the study of Muneer et al. [8], Meteorological Radiation Model (MRM) enables computation of horizontal beam and diffuse solar radiation using basic meteorological parameters — hourly dry and wet bulb temperature, atmospheric pressure and bright sunshine duration. Eighteen clear sky broadband models for estimating the DNI in Algeria have been investigated by Benkaciali et al. [9]. Solar radiation and illuminance was estimated from the meteorological parameters by Muneer et al. [10]. Power [2] employed the monthly-averaged climate turbidity data of North America and Europe to evaluate the relationships among monthly-averaged observed beam radiation, clear-sky beam irradiance, sunshine duration and, day-length. A hybrid model was designed by Yang et al. [11] for estimating monthly mean daily global radiation by employing hourly-recorded bright sunshine time in Japan. Gueymard [12,13,14] has explained about the prediction of direct solar transmittance and irradiance by using various broadband models and concluded that four models, i.e. multi-layer-weighted transmittance model, version 2 (MLWT2), Yang's model, CPCR2 and reference evaluation of solar transmittance (REST) are showing good agreement with measured values.

In the present study, three models, CPCR2, MLWT2 and REST as proposed by Gueymard [12,13,14] have been selected to compute DNI at different hours and different months of the year, for Indian tropical conditions.

## 2. Models description

### 2.1. CPCR2 model

This is the two bands model. The limits of the model have been chosen as 0.29 μm and 2.7 μm. These values approximately correspond to the average sensitivity limits of two widely used pyranometers, the Eppley PSP (0.285–2.8 μm) and the Kipp & Zonen CM6 (0.3–2.5 μm). The cut off wavelength between the UV/visible band, $B_1$, and the infrared (IR) band, $B_2$, has been set to 0.7 μm. This model has been found to be the best model in earlier studies made by Gueymard [15] and Battle et al. [16]. It is completely described by Gueymard [17]. Even though this model depends on Angstrom's wave exponent $\alpha$, it has been fixed here at 1.3.

### 2.2. MLWT2 model

This model is modified version of MLWT1, which was originally developed as both a radiation and turbidity prediction method by Gueymard [12,13,18]. MLWT2 model was based on the relatively new concept of multilayer spectral weighting, which is given by Gueymard [19] and Molineaux and Ineichen [20]. This method avoids the limitations of the Beer–Bouguer–Lambert law when applied to large spectral or broad bands. It requires intricate parameterizations because the transmittance of an atmospheric layer depends on the spectral characteristics of all the layers. This technique guarantees better overall accuracy. It also takes into account the variable effect of circumsolar radiation, which increases with turbidity and air mass. In the current work, all the basic functional form is similar to the original MLWT2 model as explained by Gueymard [12,13], except that the total $NO_2$ absorption is not taken into account. The equation of MLWT2 model is: $E_{bn} = E_{on}T_{Rg}T_oT_WT_a$. Here $E_{bn}$, is direct normal irradiance; $E_{on}$, the extra-terrestrial irradiance (i.e. the solar constant times the sun–earth distance correction factor); $T_{Rg}$, is the Rayleigh and uniformly mixed gas transmittance; $T_o$, the ozone transmittance; $T_W$, the water vapor transmittance and $T_a$, the aerosol transmittance.

### 2.3. REST model

This model has been proposed by Gueymard [12,13,14] and its form is as follows: $E_{bn} = E_{on}T_RT_gT_oT_WT_a$. Here $E_{bn}$, is direct normal irradiance; $E_{on}$, the extra-terrestrial irradiance (i.e. the solar constant times the sun–earth distance correction factor); $T_R$, is the Rayleigh transmittance; $T_g$, the uniformly mixed gas transmittance; $T_o$, the ozone transmittance; $T_W$, the water vapor transmittance and $T_a$, the aerosol transmittance.

## 3. Meteorological data

Five stations of different climatic conditions have been chosen. The stations chosen are — New Delhi representing composite climate; Kolkata, being highly industrialized, represents highly polluted, warm and humid atmosphere; Jaipur, being a desert station, represents hot and dry climate; Mumbai, being coastal city, represent warm and humid climate; Pune represents moderate climate. The solar radiation data, comprising of monthly mean hourly global and diffuse solar radiation for these Indian stations, have been collected from India Meteorology Department (IMD) Pune, India. Monthly mean values averaged over the year for all the five stations, are shown in Table 1.

**Table 1**. Geographical and climatic data of five Indian stations used in this study.

| | | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Kolkata (2002) | $T_a$ | 20 | 22 | 26 | 29 | 30 | 30 | 29 | 29 | 28 | 27 | 23 | 21 |
| [22.65°N, 88.45°E | $R_H$ | 76 | 75 | 73 | 74 | 77 | 80 | 81 | 82 | 80 | 77 | 75 | 74 |
| 6 masl] | $O_3$ | 0.24 | 0.26 | 0.26 | 0.27 | 0.28 | 0.27 | 0.26 | 0.26 | 0.26 | 0.25 | 0.25 | 0.25 |
| | $I_{gh}$ | 11.71 | 16.34 | 17.42 | 19.33 | 18.81 | 15.65 | 14.48 | 15.02 | 14.99 | 15.31 | 13.49 | 11.83 |
| Jaipur (1999) | $T_a$ | 16 | 21 | 24 | 30 | 36 | 33 | 30 | 29 | 28 | 28 | 23 | 18 |
| [26.93°N, 75.86°E | $R_H$ | 48 | 45 | 26 | 22 | 37 | 41 | 70 | 70 | 52 | 28 | 38 | 43 |
| 431 masl] | $O_3$ | 0.26 | 0.27 | 0.28 | 0.29 | 0.29 | 0.29 | 0.28 | 0.27 | 0.26 | 0.25 | 0.25 | 0.26 |
| | $I_{gh}$ | 15.22 | 17.26 | 23.48 | 26.56 | 26.20 | 24.94 | 18.77 | 19.94 | 19.36 | 17.33 | 16.02 | 13.89 |
| Mumbai (2001) | $T_a$ | 21 | 23 | 24 | 26 | 29 | 28 | 27 | 26 | 26 | 25 | 25 | 23 |
| [19.12°N, 72.85°E | $R_H$ | 67 | 68 | 72 | 75 | 78 | 81 | 87 | 87 | 86 | 82 | 75 | 71 |
| 14 masl] | $O_3$ | 0.24 | 0.26 | 0.26 | 0.27 | 0.28 | 0.27 | 0.26 | 0.26 | 0.26 | 0.25 | 0.25 | 0.25 |
| | $I_{gh}$ | 17.17 | 20.71 | 23.71 | 24.61 | 25.02 | 16.16 | 14.13 | 14.32 | 16.05 | 15.06 | 16.17 | 15.23 |
| New Delhi (1999) | $T_a$ | 15 | 16 | 21 | 27 | 31 | 35 | 34 | 32 | 29 | 26 | 21 | 17 |
| [28.63°N, 77.20°E | $R_H$ | 53 | 53 | 54 | 40 | 38 | 56 | 65 | 72 | 54 | 44 | 44 | 54 |
| 216 masl] | $O_3$ | 0.26 | 0.27 | 0.28 | 0.29 | 0.29 | 0.30 | 0.28 | 0.27 | 0.27 | 0.26 | 0.25 | 0.26 |
| | $I_{gh}$ | 10.23 | 15.05 | 20.98 | 23.45 | 22.71 | 21.25 | 18.04 | 18.88 | 16.36 | 14.35 | 14.49 | 11.67 |
| Pune (2002) | $T_a$ | 15 | 16 | 17 | 20 | 22 | 22 | 21 | 20 | 22 | 22 | 19 | 14 |
| [18.53°N, 73.85°E | $R_H$ | 48 | 45 | 26 | 22 | 37 | 41 | 70 | 70 | 52 | 28 | 38 | 43 |
| 559 masl] | $O_3$ | 0.26 | 0.27 | 0.28 | 0.29 | 0.29 | 0.29 | 0.28 | 0.27 | 0.26 | 0.25 | 0.25 | 0.26 |
| | $I_{gh}$ | 18.72 | 19.94 | 23.54 | 25.92 | 24.10 | 16.62 | 20.37 | 13.00 | 20.20 | 18.81 | 18.04 | 16.33 |

$T_a$: Monthly mean daily temperature (°C); $R_H$: Monthly mean daily relative humidity (%); $O_3$: Ozone amount (cm).
$I_{gh}$ : Monthly mean daily global radiation (MJ/m$^2$ day); masl: meter above sea level.

Global and Diffuse radiation are measured by using thermoelectric pyranometers. These pyranometers are calibrated once a year with reference to the World Radiometric Reference (WRR). The estimated uncertainty in the measured data is about ±5%. The values of Angstrom turbidity factor, $\beta$, for these locations were computed by Louche et al. [21], by taking Angstrom's wave exponent $\alpha$ as 1.3. Estimation of atmospheric turbidity for Indian locations have been studied by Narain and Garg [22] and Aher and Agashe [23].

The other meteorological data includes monthly mean hourly values of atmospheric pressure, temperature and relative humidity. This data is used to compute the amount of precipitable water in the atmosphere, by using an equation given by Leckner [24]. Data for ozone contents for the studied stations have been taken from [3]. One-year data for each of the five Indian stations was used in this study and the year for each station is shown in Table 1.

## 4. Results and discussions

A computer program was written to compute hourly value of DNI by using three different models; CPCR2, REST and MLWT2 model, for each of the 5 Indian stations mentioned earlier. The model-computed values have

been compared with the measured values in terms of percentage root mean square error, RMSE (%) and percentage mean bias error, MBE (%), and the results are shown in Table 2. The computations were not performed for the monsoon months, June to September, as during these months it is cloudy.

**Table 2**. RMSE (%) and MBE (%) of computed DNI with three models, in comparison to measured DNI, for New Delhi (1999), Pune (2002), Jaipur (1999), Kolkata (2002) and Mumbai (2001).

| Location | Month | RMSE (%) | | | MBE (%) | | |
|---|---|---|---|---|---|---|---|
| | | REST | MLWT2 | CPCR2 | REST | MLWT2 | CPCR2 |
| New Delhi | Jan | 5.76 | 3.86 | 3.15 | −4.51 | −3.26 | −2.74 |
| | Feb | 3.07 | 1.06 | 2.06 | −2.33 | −0.51 | −2.00 |
| | Mar | 2.38 | 1.00 | 2.73 | −1.86 | −0.63 | −2.72 |
| | Apr | 1.46 | 0.74 | 2.66 | −0.99 | −0.50 | −2.65 |
| | May | 0.92 | 1.59 | 2.99 | −0.28 | −1.39 | −2.96 |
| | Oct | 3.63 | 5.74 | 4.40 | −3.00 | −5.55 | −4.38 |
| | Nov | 5.19 | 2.33 | 3.19 | −4.52 | −2.12 | −3.16 |
| | Dec | 6.63 | 2.37 | 2.45 | −5.60 | −2.09 | −2.25 |
| Average | | 3.63 | 2.33 | 2.95 | −2.89 | −2.01 | −2.86 |
| Pune | Jan | 3.32 | 1.90 | 4.09 | −2.82 | −1.68 | −4.08 |
| | Feb | 2.53 | 1.51 | 3.97 | −2.13 | −1.22 | −3.95 |
| | Mar | 1.87 | 1.27 | 3.71 | −1.34 | −0.88 | −3.68 |
| | Apr | 1.65 | 1.52 | 3.75 | −1.10 | −1.12 | −3.73 |
| | May | 2.18 | 3.76 | 5.39 | −1.99 | −3.64 | −5.39 |
| | Oct | 3.19 | 4.32 | 5.57 | −2.95 | −4.21 | −5.55 |
| | Nov | 3.73 | 2.98 | 4.71 | −3.35 | −2.83 | −4.71 |
| | Dec | 3.99 | 2.67 | 4.55 | −3.62 | −2.53 | −4.54 |
| Average | | 2.81 | 2.49 | 4.47 | −2.41 | −2.26 | −4.45 |
| Jaipur | Jan | 5.72 | 1.89 | 3.70 | −4.80 | −1.61 | −3.70 |
| | Feb | 3.57 | 1.19 | 3.38 | −2.93 | −0.85 | −3.35 |
| | Mar | 2.08 | 0.92 | 2.85 | −1.33 | −0.05 | −2.81 |
| | Apr | 1.47 | 0.78 | 2.83 | −0.82 | −0.04 | −2.80 |
| | May | 1.30 | 1.04 | 3.41 | −0.89 | −0.77 | −3.40 |
| | Oct | 3.45 | 3.05 | 4.44 | −3.04 | −2.89 | −4.41 |
| | Nov | 4.96 | 2.35 | 4.00 | −4.20 | −2.01 | −3.97 |
| | Dec | 6.65 | 2.17 | 3.83 | −5.61 | −1.88 | −3.78 |
| Average | | 3.65 | 1.67 | 3.55 | −2.95 | −1.26 | −3.53 |
| Kolkata | Jan | 3.46 | 3.13 | 1.43 | −1.80 | −2.19 | −1.19 |
| | Feb | 2.40 | 1.69 | 1.64 | −1.43 | −1.25 | −1.61 |
| | Mar | 1.58 | 2.97 | 2.04 | −0.04 | −2.46 | −2.01 |
| | Apr | 1.94 | 5.49 | 3.55 | −0.18 | −4.99 | −3.43 |
| | May | 2.18 | 7.95 | 5.12 | −0.73 | −7.48 | −5.06 |
| | Oct | 2.73 | 7.32 | 3.73 | −1.87 | −7.16 | −3.72 |
| | Nov | 3.44 | 3.38 | 2.18 | −2.61 | −3.12 | −2.11 |
| | Dec | 3.85 | 2.46 | 1.25 | −2.74 | −2.04 | −1.17 |
| Average | | 2.70 | 4.30 | 2.62 | −1.43 | −3.84 | −2.54 |
| Mumbai | Jan | 3.25 | 1.83 | 2.20 | −2.57 | −1.45 | −2.19 |
| | Feb | 2.82 | 1.67 | 2.44 | −2.18 | −1.23 | −2.39 |
| | Mar | 2.18 | 2.04 | 2.63 | −1.77 | −1.82 | −2.60 |
| | Apr | 1.72 | 2.86 | 2.84 | −1.37 | −2.75 | −2.82 |
| | May | 1.59 | 3.56 | 2.99 | −1.26 | −3.45 | −2.98 |
| | Oct | 2.21 | 6.50 | 3.87 | −1.54 | −6.41 | −3.82 |
| | Nov | 3.19 | 2.81 | 2.57 | −2.73 | −2.59 | −2.55 |
| | Dec | 5.12 | 3.50 | 3.15 | −3.70 | −2.68 | −2.75 |
| Average | | 2.76 | 3.09 | 2.84 | −2.14 | −2.80 | −2.76 |

Table 2 shows that the minimum RMSE is 0.74% for MLWT2 model, in the month of April, and for New Delhi station. Similarly, table shows that minimum MBE is –0.04% for MLWT2 model, in the month April, for Jaipur.

The negative sign shows that the computed value is underestimated and the quantity shows that DNI computed by MLWT2 model in this month for the mentioned station is much closer to measured value.

The average of percentage RMSE, for the whole year, are the minimum for MLWT2 model and for stations Jaipur, followed by New Delhi and Pune and the minimum values are 1.67, 2.33 and 2.49, respectively. While for Kolkata the corresponding minimum value is in CPCR2 model and the value is 2.62 and for Mumbai the same is in REST model that is 2.76. This behavior is because of the Angstrom's turbidity factor being higher during some of the months for these two stations. Here it is observed that the percentage RMSE is lesser in most of the months for most of the stations in MLWT2 model. This shows the suitability of MLWT2 model for most of the Indian stations.

## 5. Conclusions

The performances of three models CPCR2, MLWT2 and REST have been studied at five Indian stations viz. New Delhi, Kolkata, Mumbai, Pune and Jaipur. The beam radiation at normal incidence was computed. The computed DNI was compared with measured DNI. For most of the Indian stations, RMSE percentage, averaged over a year, is the minimum for MLWT2 model as compared to, CPCR2 and REST models. This study reveals the best performance of MLWT2 model in Indian conditions.

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